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Space systems — Pressure vessels and pressurized structures — Design and operation

Systèmes spatiaux — Réservoirs et structures sous pression — Conception et fonctionnement

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

Introduction

From the beginning of the space age, hazard control has been a prime consideration in manned or unmanned flights in outer space. The rapid development of space activities and their associated technologies required the implementation of ever-increasing amounts of energy sources. Space activities can be hazardous and could cause harm to people and damage to public and private property and the environment. It is therefore necessary to develop methods and tools that can analyse hazardous situations and provide realistic recommendations in terms of safety and safety risk control. Furthermore, building space systems such as telecommunication satellites and their launch systems is costly; it is necessary to achieve high mission reliability. The variety of professional disciplines linked to these activities requires international standards to protect Earth populations against the consequences of a possible mishap caused by the failure of a highly pressurized hardware item.

There is significant history to the analysis and design of pressure vessels and pressurized structures for use in space systems. This International Standard establishes the preferred methods for these techniques in both the traditional metallic tanks, and the newer composite overwrapped pressure vessels. The emphasis is equally on adequate design and safe, as well as reliable, operation.

2.7
brittle fracture
catastrophic failure mode in a material/structure that usually occurs without prior plastic deformation and at extremely high speed

NOTE The fracture is usually characterized by a flat fracture surface with little or no shear lips (slant fracture surface)

NOTE For a surface crack, the flaw shape is expressed as $a/2c$, where a is the crack depth and $2c$ is the crack length. For a corner crack, the flaw shape is expressed as a/c, where a is the crack depth and c is the crack length

2.27
fracture control
application of design philosophy, analysis method, manufacturing technology, verification methodology, quality assurance, and operating procedures to prevent premature structural failure caused by the propagation of cracks or crack-like flaws during fabrication, testing, transportation, handling and service

2.28
fracture mechanics
engineering discipline that describes the behaviour of cracks or crack-like flaws in materials or structures under stress

2.29
fracture toughness
generic term for measures of resistance to the extension of a crack

2.30
hazard
existing or potential condition that can result in an accident

2.31
hydrogen embrittlement
mechanical-environmental process that results from the initial presence or absorption of excessive amounts of hydrogen in metals, usually in combination with residual or applied tensile stresses

2.32
impact damage
induced fault in the composite overwrap or the metallic liner of a composite overwrapped pressure vessel that is caused by an object strike on the vessel or vessel strike on an object

2.33
impact damage protector
physical device that can be used to prevent impact damage

2.34
initial flaw
flaw in a structural material before the application of load and/or deleterious environment

2.35
leak-before-burst
LBB
design concept which shows that at MEOP potentially critical flaws will grow through the wall of a metallic pressurized hardware item or the metal liner of a composite overwrapped pressure vessel and cause pressure relieving leakage rather than burst or rupture (catastrophic failure)

2.36
limit load
highest predicted load or combination of loads that a structure can experience during its service life in association with the applicable operating environments

NOTE The corresponding stress is called *limit stress*.

2.37
loading case
particular condition of pressure/temperature/loads that can occur for some parts of pressurized structures at the same time during their service life

2.38
loading spectrum
representation of the cumulating loading anticipated for the structure under all expected operating environments

NOTE Significant transportation and handling loads are included.

2.39
margin of safety
MS
margin expressed by the following equation:

$$\mathrm{MS} = \left[\frac{\text{Allowable load}}{\text{Limit load} \times \text{Factor of safety}} \right] - 1$$

NOTE Load can mean stress or strain.

2.40
maximum design pressure
MDP
highest pressure defined by maximum relief pressure, maximum regulator pressure, and/or maximum temperature, including transient pressures, at which a pressure vessel retains two-fault tolerance without failure

NOTE In this document, the term MDP is only applicable to pressure vessels.

2.41
maximum expected operating pressure
MEOP
highest differential pressure which a pressurized hardware item is expected to experience during its service life and retain its functionality, in association with its applicable operating environments

2.42
mechanical damage
induced flaw in the composite overwrap or metallic liner of a composite overwrapped pressure vessel, caused

2.46
pressure vessel
container designed primarily for the storage of pressurized fluid that fulfils at least one of the following criteria:

a) contains gas or liquid with high energy level;

b) contains gas or liquid which will create a mishap (accident) if released;

c) contains gas or liquid with high pressure level

NOTE 1 This definition excludes pressurized structures, pressure components and pressurized hardware.

NOTE 2 Energy and pressure level are defined by each project, and approved by the procuring authority (customer); if appropriate values are not defined by the project, the following levels are used:

— stored energy is 19 310 joules or greater based on adiabatic expansion of perfect gas;

— MEOP is 0,69 MPa or greater.

2.47
pressurized hardware
hardware items that contain primarily internal pressure

NOTE In this document, the term covers all pressure vessels and **pressurized structures** (2.48).

2.48
pressurized structure
structure designed to carry both internal pressure and vehicle structural loads

EXAMPLE Launch vehicle main propellant tanks, crew cabins or manned modules.

2.49
pressurized system
system which consists of pressure vessels, or pressurized structures, or both, and other pressure components such as lines, fittings, valves and bellows, which are exposed to, and structurally designed largely by, the acting pressure

NOTE Electrical or other control devices required for system operations are covered by this term.

2.50
proof factor
multiplying factor applied to the limit load or MEOP (or MDP) to obtain proof load or proof pressure for use in the acceptance testing

2.51
proof pressure
product of MEOP (or MDP) and a proof factor

NOTE The proof pressure is used to provide evidence of satisfactory workmanship and material quality and/or to establish maximum initial flaw sizes for the safe-life demonstration of a metallic hardware item.

2.52
qualification tests
required formal contractual tests used to demonstrate that the design, manufacturing, and assembly have resulted in hardware designs conforming to specification requirements

2.53
residual strength
maximum value of load and/or pressure (stress) that a cracked or damaged body is capable of sustaining

2.54
residual stress
stress that remains in a structure after processing, fabrication, assembly, testing, or operation

EXAMPLE Welding-induced residual stress.

2.55
safe life
required period during which a metallic hardware item, even containing the largest undetected crack, is shown by analysis or testing not to fail catastrophically in the expected service load and environment

2.56
sealed container
single, independent (not part of a pressurized system) container, component or housing that is sealed to maintain an internal non-hazardous environments, and has stored energy of less than 19 310 J and an internal pressure of less than 0,69 MPa

2.57
service life
period of time (or cycles) that starts with the manufacturing of the pressurized hardware and continues through all acceptance testing, handling, storage, transportation, launch operations, orbital operations, refurbishment, re-testing, re-entry or recovery from orbit and reuse that may be required or specified for the item

2.58
sizing pressure
pressure to which a composite overwrapped pressure vessel is taken with the intent of yielding the metallic liner

NOTE The sizing operation, also referred to as autofrettage, is considered to be part of the manufacturing process and is conducted prior to acceptance proof testing.

2.59
stress-corrosion cracking
mechanical-environmental induced failure process in which sustained tensile stress and chemical attack combine to initiate and propagate a crack or a crack-like flaw in a metal part

2.60
stress intensity factor
parameter used in linear elastic fracture mechanics to characterize the stress–strain behaviour at the tip of a crack contained in a linear elastic and homogeneous body

2.61
stress-rupture life
minimum time during which composite hardware maintains structural integrity, considering the combined

3 General requirements

3.1 Introduction

This clause presents general requirements for the analysis, design and verification of pressurized hardware, covering:

a) system analysis,

b) structural design and analysis,

c) material selection,

d) fatigue and /or safe-life demonstration,

e) fracture and/or damage control,

f) quality assurance, and

g) operation and maintenance.

3.2 System analysis requirements

A detailed analysis of the pressurized system in which the pressurized hardware will be operated shall be performed to establish the correct MEOP. The effect of each of the other component operating parameters on the MEOP shall be determined; failure tolerance requirements shall be considered; pressure regulator lock-up characteristics, valve actuation and water hammer, and any external loads and environments, shall be evaluated for the entire service life of the hardware.

3.3 General design requirements

3.3.1 Loads, pressures and environments

The entire anticipated load/pressure/temperature history and associated environments throughout the service life shall be determined in accordance with specified mission requirements. As a minimum, the following factors and their statistical variations shall be considered as appropriate:

a) the environmentally induced loads and pressures;

b) the environments acting simultaneously with these loads and pressures with their proper relationships;

c) the frequency of application of those loads, pressures and environments including their level, number of cycles, duration and sequence.

These data shall be used to define the design load/environments spectra that shall be used for both design analysis and testing. The design spectra shall be revised as the structural design develops and the load analysis matures.

MDP and MEOP are two baseline pressure levels that can be used for design and testing of pressure vessels. In this document, MEOP is used as the baseline pressure level. If it is required that MDP be used as the baseline pressure level, MDP may be substituted for MEOP.

3.3.2 Strength

3.3.2.1 Pressure vessels

All pressure vessels shall possess sufficient strength to withstand limit loads and simultaneously occurring internal pressures in the expected operating environments throughout their respective service lives, without experiencing detrimental deformation. They shall be able to withstand ultimate loads and simultaneously occurring internal pressures in the expected operating environments without experiencing rupture or collapse. They shall be also capable of withstanding ultimate external loads and ultimate external pressures (destabilizing) without collapse or rupture when internally pressurized to the minimum anticipated operating pressure.

All pressure vessels shall be able to sustain proof pressure in proof-testing without detrimental deformation and design burst pressure in qualification test without collapse or rupture.

When a proof or qualification test is conducted at a temperature other than design temperature, the change of material properties at the temperature shall be accounted for in determining the load/pressure. The margin of safety shall be positive and shall be determined by analysis or test at the design ultimate and design limit levels, as appropriate, at the temperatures expected for all critical conditions.

3.3.2.2 Pressurized structures

From the load/pressure time history, the critical loading cases for a pressurized structure shall be selected taking into account load/temperature/differential pressure combinations. For each critical loading case, the margin of safety shall be determined for every part of the pressurized structure, accounting for the worst combination of loads, differential pressures and temperature, with corresponding design safety factors.

All pressurized structures shall sustain the following:

a) proof pressure without gross yielding or detrimental deformation in proof-testing;

b) design burst pressure without rupture or collapse in qualification testing.

When a proof pressure test is conducted at a temperature other than the design temperature, the change in material properties at the proof temperature shall be accounted for in determining proof pressure.

Pressurized structures subject to instability modes of failure shall not collapse under ultimate loads nor degrade the functioning of any system because of elastic buckling deformation under limit loads. Evaluation of buckling strength shall consider the combined action of all stresses and their effects on general instability, local or panel instability, and crippling. Design loads for buckling shall be ultimate loads, except that any loads component that tends to alleviate buckling shall not be increased by the ultimate design factor of safety.

3.3.4 Thermal

The design of all pressurized hardware shall consider the following thermal effects, as appropriate:

a) heating rates;

b) temperatures;

c) thermal gradients;

d) thermal stresses and deformations;

e) changes in the physical and mechanical properties of the materials of construction.

3.3.5.2 Composite overwrapped pressure vessel

A detailed and comprehensive stress analysis of the composite overwrap of a new composite overwrapped pressure vessel design shall be conducted with the assumption that there is no mechanical damage existing in the overwrap. Loads and pressures shall be combined by using the appropriate design factors of safety on the individual load and pressure and comparing the results to the material allowable.

Finite element method or other proven equivalent structural analysis techniques using appropriate composite theories shall be employed to analyse the composite overwrap. Effects of ply orientation, stacking sequence and geometrical discontinuities shall be assessed. The effect of variation in material thickness and its gradients as specified in the design documentation shall be used in calculating the stresses and strains in the composite overwrap. Local structural models shall be constructed, as necessary, to augment the overall structural model in areas of rapidly varying stresses. The analysis methodology shall be verified by test results. The margins of safety shall be positive for all load conditions applied on the composite overwrap by using A-basis allowable.

3.3.5.3 Stress analysis report

Records of the stress analysis shall be maintained and shall be included in the stress analysis report, which consists of the input parameters, data, assumptions, rationales, methods, references and a summary of significant analysis results. The analysis shall be revised and updated whenever changes to input parameters occur, in order to maintain currency for the life of the program.

3.3.7 Fatigue life

3.3.7.1 Metallic hardware items

When conventional fatigue analysis is used to demonstrate the fatigue life of an unflawed metallic hardware item, nominal values of fatigue-life characteristics, including stress-life (S-N) data or strain-life (ε-N) data of the acceptance proof testing. The flaw shape ($a/2c$) in the range of 0,1 to 0,5 shall be considered for surface cracks. For corner cracks, the flaw shape (a/c) in the range of 0,2 to 1,0 shall be considered.

Nominal values of fracture toughness and fatigue crack-growth rate data associated with each alloy, temper, product form, and thermal and chemical environments shall be used in the safe-life analysis. However, if proof test logic is used for establishing the initial flaw size, an upper bound fracture toughness value shall be used in determining both the initial flaw size and the critical flaw size at fracture. A metallic hardware item which experiences sustained stresses shall also show that the corresponding maximum stress intensity factor (K_{max})

3.4.3.3 Approach A, mechanical damage protection/indication

3.4.3.3.1 General

Mechanical damage protection covers shall provide isolation from a potential mechanic damage event. When this approach is adapted, the following requirements shall apply.

3.4.3.3.2 Protective covers

The effectiveness of protective covers shall be demonstrated by testing. Protective covers or standoffs which isolate the vessel are required when personnel will be exposed to pressurized composite overwrapped pressure vessels (having stored energy level in excess of 19 310 J or containing hazardous fluids). The

3.4.5 Embrittlement control

All known embrittlement mechanisms such as hydrogen and liquid metal embrittlement, applicable to the metallic liner, fibre and resin shall be identified and controlled in the design, fabrication and operation of the composite overwrapped pressure vessel.

3.5 Material requirements

3.5.1 Metallic materials

3.5.1.1 Metallic material selection

Materials used for fabricating metallic hardware items shall be selected on the basis of proven environmental compatibility, material strengths, fracture properties, fatigue life, crack growth and stress corrosion cracking characteristics consistent with the overall program requirements. Materials' A-allowable values shall be used for metallic hardware items where failure of a single load path would result in loss of structural integrity. Materials' B-allowable values may be used for redundant structural elements where failure of one element would result in a safe redistribution of applied loads to other elements. The fracture toughness shall be as high as practicable within the context of structural efficiency and fracture resistance. For metallic hardware items to be analysed with linear elastic fracture mechanics, the following fracture properties shall be accounted for in material selection:

a) fracture toughness;

b) threshold values of stress intensity under sustained loading;

c) sub-critical crack growth characteristics under cyclic loading.

The effects of fabrication and joining processes; the effect of cleaning agents, dye (fluorescent) penetrants, coating, and proof test fluids and the effects of temperature, load spectra, and other environmental conditions shall be accounted for.

3.5.1.2 Metallic material evaluation

The materials selected for design shall be evaluated with respect to the materials processing, fabrication methods, manufacturing operations, refurbishment procedures and processes, and other pertinent factors which affect the resulting strength and fracture properties of the material in the fabricated as well as the refurbished configurations. The evaluation shall ascertain that the mechanical properties, strength and fracture properties used in design and analyses will be realized in the actual hardware and that these properties are compatible with the fluid contents and the expected operating environments. Materials that are susceptible to stress-corrosion cracking or hydrogen embrittlement shall be evaluated by performing sustained load-fracture tests when applicable data are not available

3.5.1.3 Metallic material characterization

The allowable mechanical strength, and fracture properties of all materials selected for metallic hardware items shall be characterized in sufficient detail to permit reliable and high-confidence predictions of their structural performance in the expected operating environments, unless these properties are available from reliable sources. Where material properties are not available, they shall be determined by recognized standard test methods or methods approved by the procuring authority (customer). The characterization shall produce the following strength and fracture properties for the parent metals, weld-joints, and heat-affected zones as a function of the fluid contents, loading spectra, and the expected operating environments, including proof-test environments.

a) tensile yield strength, ultimate tensile strength, and elongation;

b) plane strain fracture toughness K_{IC}, effective fracture toughness K_{IE}, and stress-corrosion cracking threshold toughness K_{ISCC};

c) fatigue crack-growth rate (da/dN) versus stress intensity factor range ΔK; and

d) fatigue data S-N (ε-N).

The test specimens and procedures utilized shall provide valid test data for the intended application. Enough tests shall be conducted so that meaningful nominal values of fracture toughness and flaw-growth rate data corresponding to each alloy system, temper, product form, thermal and chemical environments and loading spectra can be established to evaluate compliance with the safe-life requirements of 3.3.8.2. The test plan and test results shall be approved by the procuring authority (customer).

3.5.2 Composite materials

3.5.2.1 Composite materials selection

Composite material systems used for fabricating composite overwrapped pressure vessels shall be selected on the basis of proven environmental compatibility, material strength/modulus, stress-rupture life data, and compatibility with metal liner materials. If an electrically conductive fibre reinforcement is used, the design shall incorporate a means to prevent galvanic corrosion with metallic components.

The effects of fabrication processes, coatings, fluids and the effects of temperature, load spectra, and other environmental conditions which affect the strength and stiffness of the material in the fabricated configuration, shall be included in the rationale for selecting the composite material system.

3.5.2.2 Composite material system characterization

The elastic and strength properties of the composite materials selected shall be characterized in sufficient detail to permit reliable and high confidence predictions of the structural performance in their expected operating environments. Composite material systems allowable properties on the as-wrapped vessel shall be declared for each fibre/resin system. Supporting data to justify and validate the declared allowable shall include items a) and/or b) as given below, and may include supporting data from items c) and d) for quality control purposes, for checking new in-coming yarn lots:

a) previous qualification burst test results;

b) burst test results from design development tests;

c) A-basis fibre strength values from impregnated strand testing;

d) fibre manufacturer's literature and certification test results.

The supporting data shall provide justification for the declared elastic and strength properties, and sustained load behaviour consistent with the operating and non-operating environments.

Uniform test procedures shall be employed by determining material properties as required. These procedures shall conform to recognized standards. The test specimens and procedures utilized shall provide valid test data for the intended application.

The stress-rupture life data of composite materials shall be characterized if there is no existing data.

3.5.2.4 Composite material control

A material control system shall be in place to control raw materials. This shall include the following as a minimum:

a) procurement of the materials to approved specifications;

b) validation (inspection) checks for resin/resin constituent, chemistry/purity and reinforcing fibre material properties against the material specification and purchase order requirements;

c) controlled environmental storage as applicable;

d) shelf-life control.

3.6 Fabrication and process control requirements

3.6.1 Metallic hardware items

Proven processes and procedures for fabrication and repair shall be used to preclude damage or material degradation during material processing, manufacturing operations and refurbishment. In particular, special attention shall be given to ascertaining that the melt process, thermal treatment, welding process, forming, joining, machining, drilling, grinding, repair and re-welding operations, etc. are within the state-of-the-art and have been proven on similar hardware. Mechanical, physical and fracture properties of the parent materials, weld joints and heat-affected zones shall be within established design limits after exposure to the intended fabrication processes.

The dimensional stability of the materials during machining, forming, joining, welding and thermal treatments shall be ensured, and through-thickness hardening characteristics shall be compatible with the manufacturing processes. Fracture control requirements and precautions shall be defined in applicable drawings, process specifications or other appropriate documents. Detailed fabrication instructions and controls shall be provided to ensure proper implementation of the fracture control requirements. Special precautions shall be exercised throughout the manufacturing operations to guard against processing-damaged or other structural integrity degradation.

3.6.2 Composite overwrap

The composite overwrap fabrication process shall be a controlled documented process. Incorporated materials shall have certifications that demonstrate acceptable variable ranges to ensure repeatable and reliable performance. An inspection plan shall be developed per 3.7.2 to identify all critical parameters essential for verification. The amount of incorporated material on the article from the composite fabrication shall be verified.

3.7 Quality assurance requirements

3.7.1 Quality assurance program

A quality assurance program, based on a comprehensive study of the product and engineering requirements, such as drawings, material specifications, process specifications, workmanship standards, design review records and failure mode analysis, shall be established to ensure that the necessary NDI and acceptance tests are effectively performed and to verify that the product meets the requirements of this International Standard.

The program shall ensure that materials, parts, subassemblies, assemblies and all completed and refurbished hardware conform to applicable drawings and process specifications, that no damage or degradation has occurred during material processing, fabrication, inspection, acceptance tests, shipping, storage, operational use and refurbishment, and that defects which could cause failure are detected or evaluated and corrected.

3.7.2 Inspection plan

An inspection master plan shall be established prior to the start of fabrication. The plan shall specify inspection points and inspection techniques for use throughout the program, beginning with material procurement and continuing through fabrication, assembly, acceptance proof test, operation and refurbishment, as appropriate. In establishing inspection points and inspection techniques, consideration shall be given to the material characteristics, fabrication processes, design concepts, structural configuration and accessibility for inspection of flaws. For metallic hardware items, the flaw geometry shall encompass defects commonly encountered, including surface cracks, corner cracks or through cracks. Acceptance and rejection criteria shall be established for each phase of inspection and for each type of inspection technique.

3.7.3 Inspection techniques

3.7.3.1 Metallic hardware items

The most appropriate NDI technique or techniques for detecting commonly encountered flaw types shall be used for all metallic hardware items along with their flaw detection capabilities. The selected NDI techniques shall have the capability to determine the size, geometry, location and orientation of a flaw, to obtain – where multiple flaws exist – the location of each with respect to the other and the distance between them and to differentiate among flaw types – from tight cracks to spherical voids.

Two or more NDI methods shall be used for a part or assembly that cannot be adequately examined by only one method. The flaw detection capability of each selected NDI technique for metallic hardware items shall be based on past experience on similar hardware. Where this experience is not available or is not sufficiently extensive to provide reliable results, the capability, under production or operational inspection conditions, shall be determined experimentally and demonstrated by tests approved by the procuring authority (customer) on a representative material product form, thickness and design configuration.

The flaw detection capability shall be expressed in terms of detectable crack length and crack depth. The selected NDI technique should be capable of detecting allowable initial flaw size corresponding to a 90 % probability of detection (POD) at a 95 % confidence level.

3.7.3.2 Composite overwraps

As a minimum, after overwrapping, all composite overwrapped pressure vessels shall be subjected to visual inspection for detecting impact damage. State-of-the-art NDI techniques shall be selected for inspecting other mechanical damage induced on the composite overwrap as appropriate. The NDI procedures shall be based on use of multiple NDI methods to perform survey inspections or diagnostic inspections. Survey NDI inspections shall be conducted when the location of the potential damage zone is unknown, while diagnostic NDI inspections shall be performed within a localized suspect zone to characterize the type and extent of the damage. All NDI techniques, whether used as a single inspection technique or as a combination of methods, shall have the capability to detect impact and other mechanical damages that may cause the composite overwrapped pressure vessel to fail to meet the requirements of its performance specification or the requirements of this International Standard.

The damage detection capability of each selected NDI technique or combination of NDI techniques as applied to the composite overwrap shall be based on similar data from prior test programs. Where this data is not available or is not sufficiently extensive to provide reliable results, the capability — under production of operational inspection conditions — shall be determined experimentally and demonstrated by tests on representative material product form, thickness, design configuration and damage source articles.

3.7.4 Inspection data

Inspection data in the form of flaw histories shall be maintained throughout the life of the pressurized hardware. These data shall be periodically reviewed and assessed to evaluate trends and anomalies

3.7.5 Acceptance proof test

Each piece of pressurized hardware shall be proof-pressure tested to verify that the hardware has sufficient structural integrity to sustain the subsequent service loads, pressures, temperatures and environments. The temperature shall be consistent with the critical use temperature or, as an alternative, tests may be conducted at an alternate temperature if the test pressures are suitably adjusted to account for temperature effects on strength and fracture toughness. Proof-test fluids shall not pose a hazard to test personnel and shall be compatible with the structural materials in the pressurized hardware. If such compatibility data is not available, required testing shall be conducted to demonstrate that the proposed test fluid does not deteriorate the test article. Accept/reject criteria shall be formulated prior to acceptance testing. Pressurized hardware shall not leak, rupture or experience detrimental deformation during acceptance proof testing.

3.8 Operation and maintenance requirements

3.8.1 Operating procedures

Operating procedures shall be established for each pressurized hardware item. These procedures shall be compatible with the safety requirements and personnel control requirements of the facility where the operations are conducted. Step-by-step directions shall be written with sufficient detail to allow a qualified technician or mechanic to accomplish the operations. Schematics, which identify the location and pressure limits of a relief valve and burst disc, shall be provided when applicable and procedures to ensure compatibility of the pressurizing system with the structural capability of the pressurized hardware shall be established.

Prior to initiating or performing a procedure involving hazardous operations with pressure systems, practice runs shall be conducted on non-pressurized systems until the operating procedures are well-rehearsed. Initial tests shall then be conducted at pressure levels not to exceed 50 % of the nominal operating pressure until operating characteristics can be established. Only qualified and trained personnel shall be assigned to work on or with high-pressure systems. Warning signs with the hazard identified shall be posted at the operations facility prior to pressurization.

3.8.2 Safe operating limit

Safe operating limits shall be established for each pressurized hardware item, based on the appropriate analysis and testing employed in its design and qualification. These safe operating limits shall be summarized

k) permissible thermal and chemical environments;

l) admissible leakage levels versus pressure values.

For pressurized hardware items with a potential brittle fracture failure mode, the critical flaw sizes and maximum permissible flaw sizes shall also be included as appropriate. Applicable references to design drawings, detail analyses, inspection records, test reports and other backup documentation shall be indicated.

3.8.3 Inspection and maintenance

The results of the appropriate stress- and safe-life analyses shall be used in conjunction with the appropriate results from the structural development and qualification tests to develop a quantitative approach to inspection and repair. Allowable damage limits shall be established for each pressure vessel and pressurized structure so that the required inspection interval and repair schedule can be established to maintain hardware to the requirements of this document.

NDI technique and inspection procedures for reliably detecting defects and determining flaw size under the condition of use shall be developed for use in the field and at depot levels. Procedures shall be established for recording, tracking and analysing operational data as it is accumulated to identify critical areas requiring corrective actions. Analyses shall include prediction of remaining life and reassessment of required inspection intervals.

3.8.4 Repair and refurbishment

When inspections reveal structural damage or defects exceeding the permissible levels, the damaged hardware shall be repaired, refurbished or replaced, as appropriate. All repaired or refurbished hardware shall be recertified after each repair and refurbishment by the appropriate proven acceptance test procedure to verify its structural integrity and to establish its suitability for continued service.

3.8.5 Storage

When pressure vessels and pressurized structures are put into storage, they shall be protected against exposure to adverse environments that could cause corrosion, or other forms of material degradation. In addition, they shall be protected against mechanical damages resulting from scratches, dents or accidental dropping of the hardware. Induced stresses due to storage fixture constraints shall be minimized by suitable

g) acceptance and re-certification testing performed, including test condition and results;

h) analyses supporting the repair or modification which may influence future use capability.

3.9 Reactivation requirements

Pressure vessels and pressurized structures which are reactivated for use after an extensive period in either an unknown, unprotected or unregulated storage environment shall be re-certified to ascertain their structural integrity and suitability for continued service before commitment to flight. Re-certification tests for pressurized hardware shall be in accordance with the appropriate re-certification test requirements. A purposeful inspection for corrosion and incidental damage prior to re-certification testing shall be performed.

3.10 Service-life extension requirements

For LBB non-hazardous pressurized hardware, the allowable service life can be determined by conventional fatigue analysis or testing. It can be extended without additional test or inspection, if there is available adequate data such as actual pressure, loads and environments from the past period of service life.

Actual loading spectrum and environmental data should be used as the fatigue equivalent condition of the qualification test by using analysis or both analytical and experimental methods. The part of cumulative damage corresponding to the past period of a service life should be evaluated. For brittle or LBB hazardous pressurized hardware, the allowable service life shall be determined by fracture mechanic analysis.

4 Specific requirements

4.1 General

This clause presents specific requirements for pressurized hardware. Included are factor of safety requirements, failure mode demonstration requirements, cyclic and burst test requirements, vibration test requirements, safe-life demonstration requirements and other requirements specifically applicable to special items.

4.2 Pressure vessels

4.2.1 General

Two types of pressure vessel are covered in this document: metallic pressure vessels and composite overwrapped pressure vessels. The specific requirements for these two types of pressure vessel are delineated in the following.

4.2.2 Metallic pressure vessels

4.2.2.1 General approach

Based on the results of the failure mode determination, one of two verification approaches shall be satisfied:

a) **Approach 1:** LBB with leakage of the contents not creating a condition which could lead to a mishap (such as toxic gas venting or pressurization of a compartment not capable of the pressure increase);

b) **Approach 2:** brittle fracture failure mode or hazardous LBB failure mode in which, if the metallic pressure vessel leaks, the leak will cause a hazard.

The verification requirements for Approach 1 are given in 4.2.2.2 and the verification requirements for Approach 2 in 4.2.2.3.

4.2.2.2 Metallic pressure vessels with non-hazardous LBB failure mode

4.2.2.2.1 LBB demonstration

A metallic pressure vessel containing non-hazardous fluid and exhibiting LBB failure mode is considered *not fracture critical*. Analysis or test per requirements specified in 3.3.6 shall demonstrate the LBB failure mode.

4.2.2.2.2 Design factor of safety

Metallic pressure vessels which satisfy the non-hazardous LBB failure mode criterion may be designed conventionally, wherein the design factors of safety and proof test factors are selected on the basis of successful past experience. Unless otherwise specified, the minimum burst factor shall be 1,5.

The factor of safety to the external (supporting) loads shall be same as that assigned to the primary structures. The minimum ultimate safety factor to the external loads shall be 1,25 for unmanned systems and 1,4 for manned systems.

4.2.2.2.3 Fatigue-life demonstration

The fatigue life of the metallic pressure vessel with a non-hazardous LBB failure mode shall be demonstrated by analysis or test as specified in 3.3.7.

4.2.2.2.4 Qualification test requirements

Qualification tests shall be conducted on flight-quality metallic pressure vessels to demonstrate structural adequacy of the design. The test fixtures, support structures and methods of environmental application shall

Table 1 — Qualification pressure test requirements

Test item	No yield after	No burst[a]
Vessel No. 1[b]	—	Burst factor × MEOP
Vessel No. 2	Pressure: 1,5 × MEOP Cycle: 2 × predicted number or Pressure: 1,0 × MEOP Cycle: 4 × predicted number	Burst factor × MEOP

[a] Unless otherwise specified, after demonstrating no burst at the design burst pressure test level, increase pressure to actual burst of vessel.

[b] Test may be deleted at discretion of the procuring authority (customer).

4.2.2.2.5 Acceptance test

Acceptance tests shall be conducted on every metallic pressure vessel before commitment to flight. Accept/reject criteria shall be formulated prior to testing. The test fixtures and support structures shall be designed to permit application of all test loads without jeopardizing the flight worthiness of the test article. The following are required as a minimum.

a) Nondestructive inspection

A complete inspection by the selected NDI technique shall be performed prior to the proof pressure test to establish the initial condition of the hardware. The NDI prior to proof test can be substituted for that of the manufacturing process.

b) Proof-pressure test

Every metallic pressure vessel shall be proof-pressure tested to verify that the materials, manufacturing processes and workmanship meet design specifications, and that the hardware is suitable for flight. Maximum duration of proof test shall not exceed the appropriate time to avoid potential crack propagation due to a stress corrosion cracking mechanism.

The following is the guideline for the minimum proof-pressure (p_{proof}) levels:

— p_{proof} = (1 + burst factor)/2 × (MEOP), for a burst factor less than 2,0;

— p_{proof} = 1,5 × (MEOP), for a burst factor equal or greater than 2,0.

c) Leak test

The leak test shall be conducted after the proof pressure test.

4.2.2.2.6 Re-certification test

All refurbished metallic pressure vessels shall undergo the same acceptance tests as specified for new vessels, in order to verify their structural integrity and to establish their suitability for continued service before commitment to flight. Deviations from this requirement are only allowed if it can be demonstrated that the refurbished parts of the metallic pressure vessel are not affected by the corresponding tests.

Metallic pressure vessels that have exceeded the specified storage environment (temperature, humidity, time, etc.) shall also be re-certified by the acceptance test requirements for new hardware.

4.2.2.2.7 Special provision

In cases involving a design that will be used in a low cycle, single application, a proof test to each flight unit to a minimum of 1,5 times MEOP and a conventional fatigue analysis showing a minimum of 10 design lifetimes may be used in lieu of the required pressure testing according to 4.2.2.2.4 b). The implementation of this

4.2.3 Composite overwrapped pressure vessels

4.2.3.1 General approach

All composite overwrapped pressure vessels shall be classified by their applications and the liners' failure modes. Based on the results of failure mode determination and the contained fluids, they shall be classified as

a) composite overwrapped pressure vessel with non-hazardous LBB failure mode, or

b) composite overwrapped pressure vessel with brittle fracture or hazardous LBB failure mode.

4.2.3.2 Composite overwrapped pressure vessels with non-hazardous LBB failure mode

4.2.3.2.1 LBB demonstration

For composite overwrapped pressure vessels with elastically responding metallic liners, the LBB failure mode shall be demonstrated by analysis or test. If by analysis, the requirements specified in 3.3.6.2 shall be met.

For composite overwrapped pressure vessels with plastically responding metallic liners, the LBB failure mode demonstration shall be by test only. LBB demonstration testing shall be conducted in accordance with 3.3.6.3.

4.2.3.2.2 Design factor of safety

Unless otherwise specified, the design burst factor shall be 1,5 as a minimum. Safety factor on external (supporting) loads shall be as assigned to primary structures supporting the pressurized system as a minimum. The minimum ultimate safety factor on external loads shall be not lower than 1,25 for unmanned systems and 1,4 for manned systems.

4.2.3.2.3 Fatigue life

The fatigue-life requirements specified in 3.3.7 shall be met.

4.2.3.2.4 Stress-rupture life

The stress-rupture-life requirements specified in 3.4.2 shall be met.

4.2.3.2.5 Damage control

The damage control requirements specified in 3.4.3 shall be met.

4.2.3.2.6 Qualification test

The qualification test requirements for composite overwrapped pressure vessels are identical to those of metallic pressure vessels except for the pressure cycle test and the burst test. The following delineates the pressure cycle test and burst test requirements.

a) Pressure cycle test

The pressure cycle test shall be performed in accordance with Table 2. The fluids shall be compatible with the structural materials used in the COPV and shall not pose a hazard to test personnel. The requirement for application of external loads in combination with internal pressures during testing should be evaluated based on the relative magnitude and/or destabilizing effect of stresses due to the external load. If limit combined tensile stresses are enveloped by test pressure stresses, the application of external loads shall not be required. If application of external loads is required, the loads shall be cycled to limit level for at least four times the predicted number of operating cycles of the most severe design condition. Examples are the destabilizing load with constant minimum internal pressure or maximum additive load with a constant maximum expected operating pressure. Pressure cycle tests shall be conducted at the maximum temperature for each pressure cycle event. Otherwise, the temperature effects on material properties shall be accounted for in the test pressure.

Table 2 — COPV qualification test pressure cycle requirements

Test item	Life cycle test, demonstrate no detrimental effects	Burst test, demonstrate no burst at[a]
Vessel No. 1[b]	—	Burst factor × MEOP
Vessel No. 2	Cycle from zero differential pressure to acceptance proof pressure level and back to zero differential pressure for at least 4 times the number of planned proof cycles[c] and a) or b) as follows b) cycle from zero differential pressure to 1,0 × MEOP and back to zero differential pressure for at least four times the number of planned pressure cycles that would be expected in one service life; c) cycle from zero differential pressure to the maximum pressure in planned pressure cycles in sequence and back to zero differential pressure for at least four times the number of planned pressure cycles in one service life [c, d].	Burst factor × MEOP

NOTE For the purpose of clarification, "zero pressure" can be as high as 5 % of the test pressure.

[a] Unless otherwise specified by the procurement agency and/or launch site safety office having jurisdiction, after demonstrating no burst at the design burst pressure test level, increase pressure to actual burst of vessel.

[b] Test may be deleted at discretion of the procuring authority (customer).

[c] If there are other proof tests in addition to the acceptance proof test specified in 4.2.3.2.7 b), e.g. a proof pressure test for the pressure subsystem, the other proof pressure tests shall be included.

[d] Only cycles having a peak operating pressure that creates a liner tensile stress (exceeds the compressive metal liner pre-stress as imposed by the overwrap, as a result of vessel autofrettage), will be considered in the life cycle test.

b) Burst test

After the pressure cycle and leak tests, the composite overwrapped pressure vessel shall be pressurized to the design burst pressure level and shall be held for a minimum of 30 s. The vessel shall not rupture at, or prior to, the end of the 30 s hold time. Upon successful completion of the hold period, the pressure shall be increased at a controlled rate until vessel burst or collapse. Where the vessel mounting induces axial or radial restrictions on the pressure driven expansion of the vessel, the burst test fixture shall simulate the structural response or reaction loads of the flight mounting. Burst tests shall be conducted at the worst case temperature. Otherwise, the temperature effects on material properties shall be accounted for in the test pressure.

4.2.3.2.7 Acceptance tests

Acceptance tests shall be conducted on every composite overwrapped pressure vessel before commitment to flight. Accept/reject criteria shall be established prior to tests. The test fixtures and support structures should be designed to permit application of all test loads without jeopardizing the flight-worthiness of the test article. The following tests conducted in the order specified are required as a minimum:

a) NDI

A visual inspection shall be performed to inspect potential impact damage, as a minimum.

b) Acceptance proof pressure test

Every composite overwrapped pressure vessel shall be subjected to one cycle acceptance proof pressure test (from zero differential pressure to predetermined proof pressure level and back to zero differential pressure) to verify that the materials, manufacturing processes and workmanship meet design specifications, and that the hardware is suitable for flight. Unless otherwise specified, the minimum acceptance proof pressure shall be 1,25 × MEOP. Proof-test fluids shall be compatible with the structural materials used in the composite overwrapped pressure vessel. If such compatibility data is not available, required testing shall be conducted to demonstrate that the proposed test fluid does not cause the test article to deteriorate. Unless otherwise stated, the duration of the proof test should be 5 min. After the proof test, a leak check shall be performed.

4.2.3.3 Composite overwrapped pressure vessels with brittle failure mode or hazardous LBB failure mode

4.2.3.3.1 Design factor of safety

The design factor of safety requirement specified in 4.2.3.2.2 shall be met.

4.2.3.3.2 Safe-life demonstration

Safe life instead of fatigue life of the metallic liner of the composite overwrapped pressure vessel shall be demonstrated in accordance with 3.3.8. For a composite overwrapped pressure vessel, that contains hazardous fluids, leak is not acceptable.

4.2.3.3.3 Stress-rupture-life requirements

The stress-rupture-life requirements specified in 3.4.2 shall be met.

4.2.3.3.4 Damage control requirements

Damage control requirements specified in 3.4.3 shall be met.

4.2.3.3.5 Qualification test requirements

The qualification test requirements specified in 4.2.3.2.6 shall be met.

4.2.3.3.6 Acceptance test

The acceptance test requirements for composite overwrapped pressure vessels with brittle fracture liners or containing hazardous fluids are identical to those for composite overwrapped pressure vessels that exhibit non-hazardous LBB failure mode as specified in 4.2.3.2.7, except that the selected NDI shall be able to detect cracks or crack-like flaws in the metallic liners of the composite overwrapped pressure vessel prior to the wrapping of composite materials.

4.3 Pressurized structures

4.3.1 Metallic pressurized structures

4.3.1.1 General approach

For pressurized structures made of metallic materials, such as the aluminum fuel tanks of a launch vehicle, the design approach may be based on successful past experience when appropriate. However, the analysis and verification requirements specified herein shall be met.

4.3.1.2 Pressurized structures with non-hazardous LBB failure mode

4.3.1.2.1 General

The LBB failure mode shall be demonstrated in accordance with 3.3.6

4.3.1.2.2 Factor of safety requirements

Unless otherwise specified, metallic pressurized structures that satisfy the LBB failure mode may be designed with a minimum ultimate safety factor of 1,25 for unmanned systems and 1,40 for manned systems.

4.3.1.2.3 Fatigue-life demonstration

The fatigue-life requirement specified in 3.3.7 shall be met.

4.3.1.2.4 Qualification testing

Qualification testing shall be conducted on flight-quality hardware to demonstrate the structural adequacy of the design. Because of the potential test facility size limitation, the qualification testing may be conducted on the component level, provided that the boundary conditions are correctly simulated. The test fixtures, support structures and methods of environmental application shall not induce erroneous test conditions. The sequences, combinations, levels and duration of loads, pressure and environments shall demonstrate that design requirements have been met. Qualification testing shall include pressure cycle testing and burst testing. The following delineates the required tests.

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4.3.1.2.6 Recertification test requirements

See 4.2.2.2.6.

4.3.1.2.7 Special provision

For pressurized structures such as crew cabins and manned modules, the design burst pressure capability may be demonstrated, on properly instrumented and representative development or flight articles, by verification of compliance with the analytical structural model for the design and application. The implementation of this option requires prior approval by the procurement authority (customer).

4.3.1.3 Pressurized structures with hazardous LBB or brittle failure mode

4.3.1.3.1 Factor of safety

See 4.3.1.2.2.

4.3.1.3.2 Safe-life requirements

The safe-life demonstration requirements specified in 3.3.8 shall be met.

4.3.1.3.3 Qualification testing

Qualification testing shall include pressure cycle testing, leak testing and burst testing. The leak testing shall be conducted after pressure cycle testing. The requirements specified in 4.3.1.2.4 for pressure cycle testing and burst testing shall be met.

4.3.1.3.4 Acceptance test requirements

The acceptance test requirements for pressurized structures which exhibit brittle fracture failure mode or hazardous LBB failure mode shall be identical to those with non-hazardous LBB failure mode as defined in 4.3.1.2.5, except that the selected NDI techniques shall be capable of detecting flaws or cracks smaller than the allowable initial flaw size as determined by safe-life analysis. Furthermore, NDI shall also be performed on fracture critical welds after proof testing.

4.3.1.3.5 Re-certification test requirements

The requirements specified in 4.3.1.2.6 shall be met.

4.3.1.3.6 Special provision

Requirements shall be the same as those specified in 4.3.1.2.7, except that the fracture mechanics safe-life analysis shall be performed. The flaw sizes and shapes shall be based on the proof test or selected NDI method(s).

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